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Joint Consideration of Layout and Pipe Sizes for Water Distribution Network Design with Reliability

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Abstract

In a looped water distribution network (WDN) alternate paths are available for supply in case a pipe fails and isolated from the network. The provision of minimum size or minimum flow carrying capacity of each pipe in a least-cost design of WDNs, or deciding layout of a looped WDN such that at least two-pipes are connected at each node may assure connectivity but not sufficient capacity of the network to meet demands during failure of any pipe. Reliability of looped network increases with increase in number of pipes at each node, or increase in pipe sizes; however, the cost also increases. Thus, reliability-based design should consider both layout and pipe sizes optimization. Methodologies based on entropy have been suggested for selection of layout and design to consider reliability [1, 2]. A new methodology, based on flow uniformity in the network, is attempted for the selection of network layout. The flow-uniformity is assessed through variance of flow-series. It is observed that in a branched network, the variance of pipe-flows is maximum; and the reliability of the network increases as the variance decreases by adding loop-forming links. A heuristic methodology is suggested to obtain a layout with minimum variance. The layout so selected is optimally designed using linear programming. The methodology is applied to a simple problem and cost and reliability values are compared. Further, a network from the literature [3] is considered. The reliability consideration is observed to have a layout with more number of pipes as compared to that obtained for minimum cost design.

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1. Introduction

Looped networks are preferred over branched networks as they provide alternate path in case of failure of any one pipe. However, to minimize the cost of WDN, the loop-forming links are provided with minimum size, or such that they carry some minimum discharge. Obviously, such minimum cost looped networks have low reliability. The reliability at a node increases with the increase in number of pipes connected to it as number of alternative paths would be available and the impact of failure of any one of the pipe would be less. This, however, increases the cost of the network. Therefore, a network is considered to have sufficient topological redundancy if all the nodes are connected by at least two pipes. Further, to have minimum impact of a failure, it is desired that the flow carrying capacities of each of the pipe connected to a node are equal. However, due to different nodal demands such a flow-distribution in a WDN is not possible; thus such design is practically impossible. Therefore, maximum uniformity in flow should be achieved in any flow distribution. Martinez et al. [4] suggested Chiong's model [5] for flow-distribution and used it for design of looped water networks considering the cost of pipe, cost of energy, cost of repairs and cost of supplying water to affected consumers during failure of pipe. Gupta et al. [6] compared various flow distribution models and observed superiority of Chiong's model over other available models for network design with redundancy. Gupta et. al [7] used the Chiong's model for upgrading the network reliability at minimum cost. In this paper, the concept is extended herein to select layout of a WDN to have maximum reliability. One small network and one example problem from Morgan and Goulter [3] is considered to illustrate the application of methodology and compare the result.

Nomenclature

DSR	demand satisfaction ratio
N	number of pipes in the network
$\bar{Q}$	mean of the flows
Q	flow in a pipe
V_Q	variance of pipe flow
WDN	water distribution network

2. Philosophy and Proposed Methodology

Consider a looped network which is converted to a branched network using minimum spanning tree or path concept (Bhave 2003). The variance of pipe-flow-series is maximum in such a branched water distribution network as flow in all loop forming links are zero. If a pipe is connected between two nodes to form a loop in the network, the variance may reduce. This reduction is due to the fact that one of the loop-forming link is assigned some flow in place of zero flow. However, with the further addition of pipes between nodes following will happen: (1) one of the zero-flow is changed to some flow; and (ii) redistribution of flows in existing loops will take place. This may cause increase in variance. Thus, change in variance would be different for different possible loop conversions. Comparing the reduction in variance for different loop conversions, the best is considered as one that provided maximum reduction in variance. This iterative method of loop identification is continued till all the available options are exhausted or no further reduction in variance is possible. In case all options are utilized, the complete network is best from reliability consideration; else some of the links can be eliminated from the network. The step-wise methodology for addition of loop-forming links is as follows:

1. Convert the loop network into a branched network using path concept.